VLT observations of the solitary millisecond pulsar PSR J2124$-$3358

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ABSTRACT

About 100 millisecond (ms) pulsars have been identified in the Galaxy, and only $\approx 10\%$ of them are solitary, i.e. without a binary companion. Nothing is known on the optical emission properties of millisecond pulsars. Observations of *solitary* millisecond pulsars are the only way to detect their faint optical radiation, otherwise buried by the brighter white dwarf companion. As in the case of solitary, non millisecond pulsars, an X-ray detection represents the first step for a follow-up identification campaign in the optical. Among the X-ray detected millisecond pulsars, PSR J2124$-$3358 stands out as an ideal case because it is very close (≤ 270 pc) and little absorbed. Here, we report on recent VLT observations of the PSR J2124$-$3358 aimed at the identification of its optical counterpart. No optical emission from the pulsar has been detected down to a limiting flux of $V \sim 27.8$.

Introduction

The about 1500 radio pulsars known to date are interpreted as rapidly spinning and strongly magnetized neutron stars which are radiating at the expense of their rotational energy. Millisecond pulsars form a separate group among the rotation-powered pulsars. They are distinguished by their small spin periods (≤ 20 ms) and their high spin stability ($\dot{P} \approx 10^{-18} - 10^{-21}$ s s^{-1}), with corresponding spin-down ages $P/2\dot{P}$ of typically $10^9 - 10^{10}$ years. Only $\approx 20\%$ of the galactic millisecond pulsars are solitary, including PSR B1257+12 which is in a planetary system. The rest are in binaries, usually with a low-mass white dwarf companion. Optical observations of *binary* millisecond pulsars have so far only allowed to detect the companion star (see, e.g., Danziger et al. 1995; Lundgreen et al. 1996) and to constrain the global evolution of the binary systems. In no case it was possible to detect the fainter optical emission from the neutron star which is buried by the brighter companion. Optical observations of solitary millisecond pulsars thus are the only chance to explore the optical emission properties of these peculiar objects.

The optical emission of solitary millisecond pulsars can be ascribed either to magnetospheric or thermal radiation from the neutron star surface. However, unless some reheating mechanism is at work, optical thermal radiation is expected to be virtually undetectable for old ($\approx 10^9$ yrs), cooled off, neutron stars and magnetospheric radiation appears the most likely emission process. From the model developed by Pacini (1971), the magnetospheric emission is expected to depend on the pulsar's spin parameters according to the relation $L_{opt} \propto B^4 P^{-10}$. Although valid for young pulsars such a dependance, as well as any breakdown with the pulsar's age, is still unclear for older neutron stars. Detecting optical emission from millisecond pulsars, i.e. short period and low $\dot{P}$ objects, would thus be of paramount importance to define a general framework.

As for classical, i.e., isolated non-millisecond pulsars, a detection at soft X-ray energies represents an important indicator that the object is likely detectable at optical wavelength. Currently, soft X-ray emission have been discovered from a number of galactic solitary millisecond pulsars but only for a few of them X-ray

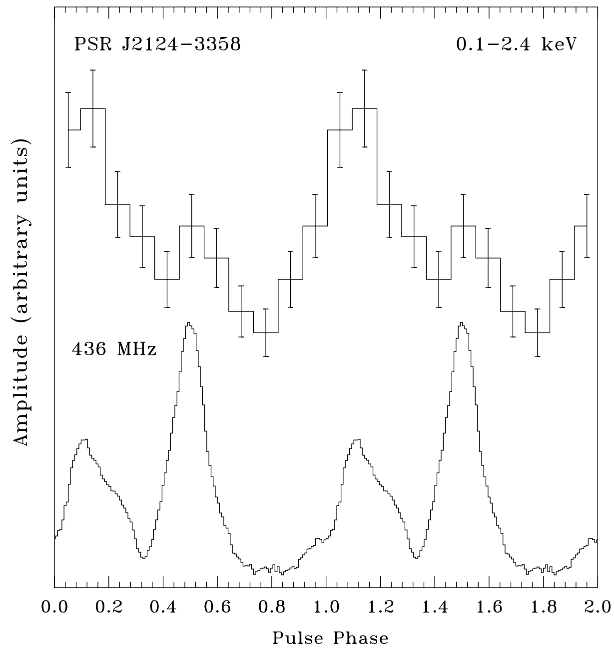

Fig. 1. Comparison between the X-ray and radio pulse profiles of PSR J2124−3358. The gross similarities in the pulse structure is obvious and indicates that the emission process which powers the X-ray pulsations is closely related to the radio emission ones. This clearly suggests a magnetospheric origin also for the X-ray emission.

pulses have been detected (see Becker & Trümper 1999; Becker & Aschenbach 2002).

PSR J2124−3358

One of the most interesting objects is PSR J2124−3358. The pulsar was identified in radio during the Parkes 436 MHz southern survey (Bailes et al. 1997). Its measured $\dot{P}$ of $1.096\ 10^{-20}$ s s^{-1} gives an age of 7.2 billion years, a magnetic field of $2.3\ 10^{8}$ G and a rotational energy loss of $3.5\ 10^{33}$ ergs s^{-1}. PSR J2124−3358 was discovered in soft X-ray energies during a recent study of galactic isolated millisecond pulsars using the *ROSAT* HRI (Becker & Trümper 1999). Its X-ray emission was found to be pulsed at the radio period, with a sharp double-peaked pulse profile. The shape of the X-ray pulse profile was considered a strong evidence that the X-ray emission from this millisecond pulsar is dominated by non-thermal emission (cf. Becker & Trümper 1999). Indeed, the X-ray lightcurve exhibits a double peak structure remarkably similar to the pulse profile observed in the radio domain at 436 MHz (Bailes et al. 1997; Becker & Trümper 1999). Figure 1 shows a comparison between the PSR J2124−3358 pulse profiles as oberved in the X-ray and radio bands. The interpretation in terms of magnetospheric emission has been later supported by ASCA observations which showed that the pulsar spectrum in the 0.5-10 keV interval is compatible with a power law (Sakurai et al. 2001).
PSR J2124−3358 is therefore one of the most promising millisecond pulsars for optical studies as it turns out to be one of the brightest solitary millisecond pulsars detected at X-ray energies. Its close distance of about 270 pc (Cordes & Lazio 2002) together with its small Hydrogen column absorption of $\sim 2 - 5\ 10^{20}$ cm^{-2} (Becker & Trümper 1999) also make this object a natural target for subsequent optical observations.

Observations

The first optical observations of the PSR J2124−3358 field were performed in July 1998, shortly after the detection of the pulsar in X-rays. Observations were performed with the ESO NTT using the ESO Multi Mode Instrument (EMMI) in its Blue Arm configuration with a pixel size of 0.37" (field of view $6.2' \times 6.2'$). A total of six exposures (1200s each) were acquired through a B filter. Single images were reduced us-

ing standard MIDAS recipes and combined using a median filter algorithm. Photometric calibration was computed through short exposures of Landolt's fields. Unfortunately, since all the exposures of the PSR J2124−3358 field were affected by bad atmospheric conditions and by a seeing constantly above 1.5" it was not possible to reach a detection limit fainter than $B \simeq 25$ (Becker & Mignani, unpublished).
The field of PSR J2124−3358 was observed again between August and September 2001 using the ESO VLT/Antu telescope operated in Service Mode from the Paranal Observatory (Becker et al. 2002a). Imaging was performed using the FOcal Reducer and Spectrograph 1 (FORS1) camera operated in its standard resolution mode, with a pixel size of 0.2" and a corresponding field of view of $6.8' \times 6.8'$. Images were taken through the U ($\lambda = 3660$Å, $\Delta\lambda = 360$Å), B ($\lambda = 4290$Å, $\Delta\lambda = 880$Å) and V ($\lambda = 5540$Å, $\Delta\lambda = 1110.5$Å) passbands to allow for a significant spectral coverage. For each filter, sequences of 12 repeated exposures were obtained for a total integration time of 9360 s in U and 6000 s in B and V. The detailed summary of the observations is listed in Table 1. To allow for relative adjustments in the flux calibration, one exposure of each sequence was obtained under photometric conditions. The pulsar field was always observed close to the minimum airmass with average values of 1.10 (U), 1.09 (B) and 1.03 (V). Seeing conditions across all the exposures varied between ~ 0.6" and ~ 1.0".
Standard reduction steps were applied through the FORS1 image reduction pipeline. For each night, master bias and sky flats were used for debiassing and flatfielding. Flux calibration was computed using the extinction and color-corrected photometric zero-points routinely computed for each night. For each passband, sequences of repeated exposures were finally co-added by applying a median filter algorithm to reject cosmic ray hits.

Date	Filter	No. of exp.	Exposure(s)	seeing (")	airmass
2001 August 12	U	3	780	1.0"	1.33
2001 August 13	U	9	780	0.8"	1.026
	B	1	500	0.8"	1.034
	V	1	500	0.8"	1.028
2001 Sep 14	B	6	500	0.58"	1.134
	V	6	500	0.63"	1.046
2001 Sep 17	B	5	500	0.52"	1.054
2001 Sep 18	V	5	500	0.96"	1.017

Table 1. Summary of the optical observations of the field of PSR J2124−3358 obtained with the FORS1 instrument at VLT/Antu. All the observations were taken with the same instrument configuration. For each observation, the columns give the observing date, the filter, the number of exposures, the integration time per exposure, the average seeing conditions, and the average airmass during the exposure sequence.

Results

Since the first hint to claim the optical identification of the pulsar comes from a positional coincidence with a potential counterpart, an accurate astrometry of the field is a key issue. In order to register the very accurate (down to few milliarcseconds) pulsar position (Gaensler, Jones and Stappers 2002) on the FORS1 images, we have recomputed the FORS1 astrometry using as a reference the positions of stars selected from the Guide Star Catalogue II, which have an intrinsic absolute astrometric accuracy of $\approx 0.35''$ per coordinate. After identifying a number of well suited GSC-II objects in the co-added V-band image, the pixel-to-sky coordinate transformation has been computed using the program ASTROM[1]. The final precision on the astrometric fit was $\sim 0.09''$ in both RA and Dec. To this value we then added an error of $0.17''$ due to the propagation of the intrinsic absolute errors on the GSC-II coordinates.

[1]http://star-www.rl.ac.uk/Software/software.htm

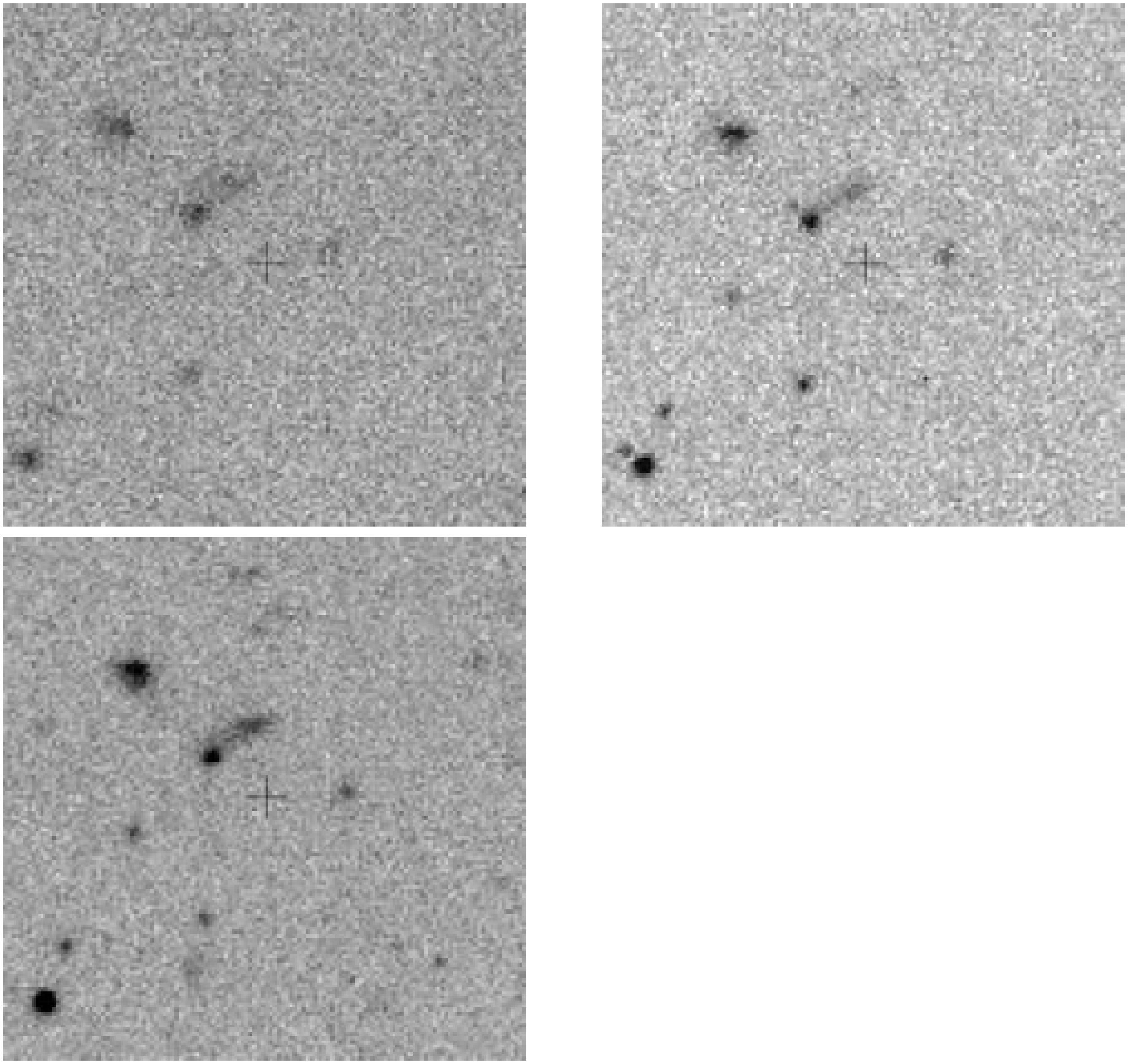

Fig. 2. From top left to bottom left: U, B and V-band images of the field of the millisecond pulsar PSR J2124−3358 obtained with the FORS1 instrument of the VLT-Antu. North to the top, East to the left. The images, $25" \times 25"$, are obtained by the median of all the available exposures (see Table 1). The cross marks the nominal radio position of the pulsar computed according to the more recent radio coordinates (see Gaensler, Jones and Stappers 2002). The sizes of the cross arms is set to 1 arcsec, i.e., 5 times the overall uncertainty on the pulsar position

Since the error on the pulsar position is negligible, the overall uncertainty in the registration of the radio coordinates on the optical frames is dominated by the accuracy of the astrometric catalogue used as a reference and by the rms of the astrometric fit. Taking both factors into account, we finally ended up with an uncertainty of $\approx 0.2''$ in both RA and Dec. Any additional uncertainty on the pulsar position due to its known proper motion of $\mu = 52.6$ mas yr^{-1} (Cordes, Jones and Stappers 2002) is certainly within our global error budget. We note that the GSC-II astrometry was tied to the extragalactic radio source frame (ICRF), thus our position should not be significantly affected by any systematic offset between the radio and optical reference systems. Our astrometry is shown on the co-added UBV-band images (Figure 2). No object is detected at the pulsar position down to 3σ limiting magnitudes of $U \simeq 26$, $B \simeq 27.7$ and $V \simeq 27.8$. Thus, we assume these values as upper limits on the optical flux of the pulsar. By scaling for the assumed distance of 270 pc (Cordes & Lazio 2002), our upper limits imply an optical luminosity $L_{opt} \leq 2.5\ 10^{26}$ ergs s^{-1}, which makes PSR J2124$-$3358 intrinsically fainter than the old ($\approx 10^6 - 10^7$ yrs) *ordinary* pulsars PSR B1929+10 and PSR B0950+08 (Pavlov et al. 1996).

Conclusions

We have reported on the first, deep, optical observations of the field of the millisecond pulsars PSR J2124$-$3358 performed with the ESO VLT. The pulsar is undetected down to a flux limit of $V \sim 27.8$, the deepest obtained so far for an object of this class. Unfortunately, this result adds to the list of non-detections of millisecond pulsars deriving from (shallower) observations recently performed with the VLT, namely PSR J1024$-$0719, PSR J1744$-$1134 (Sutaria et al. 2002) and PSR J0030+0451 (Becker et al. 2002b). Future observations of these objects in the near-UV with the HST will probably offer higher chanches of detection.

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